Heavy Flavor Production in CDF II Detector

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1 – Outline

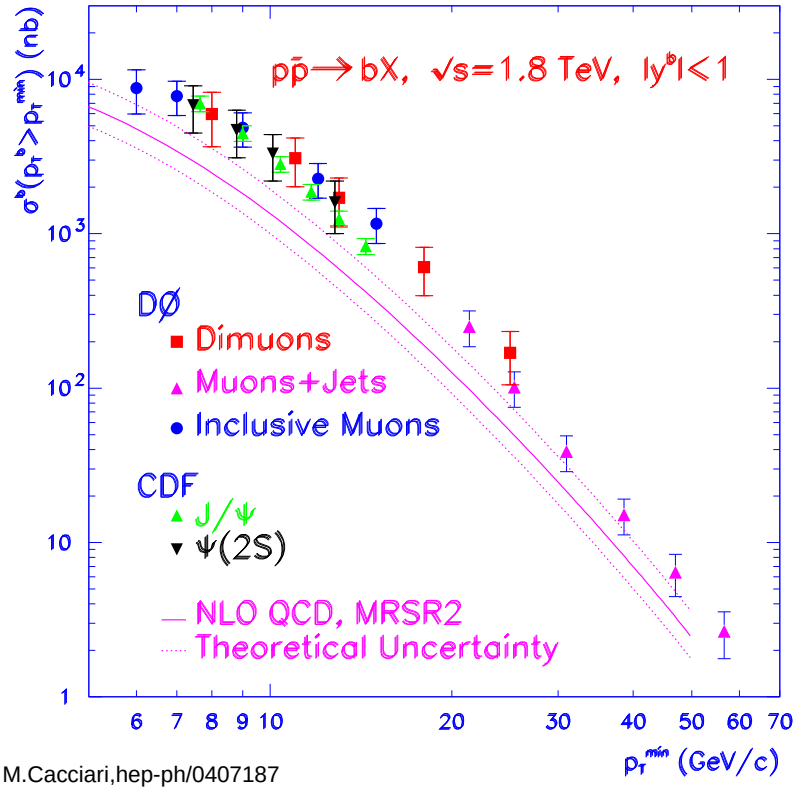
- √ Introduction: history
- √ Theoretical approach.
- √ Experimental Measurements with Heavy Quark Hadrons in decay modes
  - Exclusive hadronic decay modes of charm D- mesons.
  - Inclusive $B \to J/\psi\, X$ with $J/\psi \to \mu^+\mu^-$ muon mode
- √ Experimental Measurements with inclusive b-quark Tagged Jets
- √ Conclusions.

2 – Introduction: history

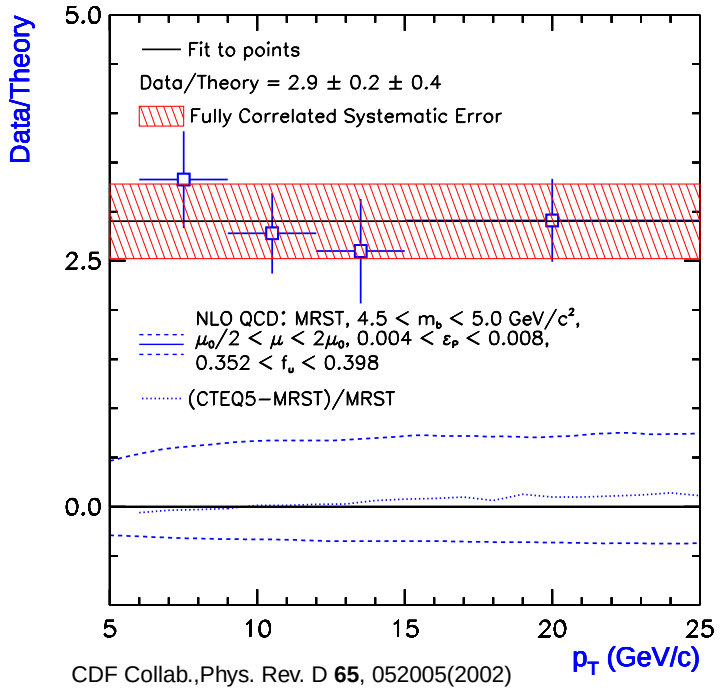
⇒ **CDF & D0 inclusive measurements as of 1995. The exper. points begin only**at $p_T > 6.0\,\mathrm{GeV}/c$.

⇒ **CDF Run I** $B^+ \to J/\psi\, K^+$ **(2001) comparison with a theory as of 2001:**

$2.9 \pm 0.2(stat \oplus syst_{p_T}) \pm 0.4(syst_{fc})$ times higher than NLO QCD

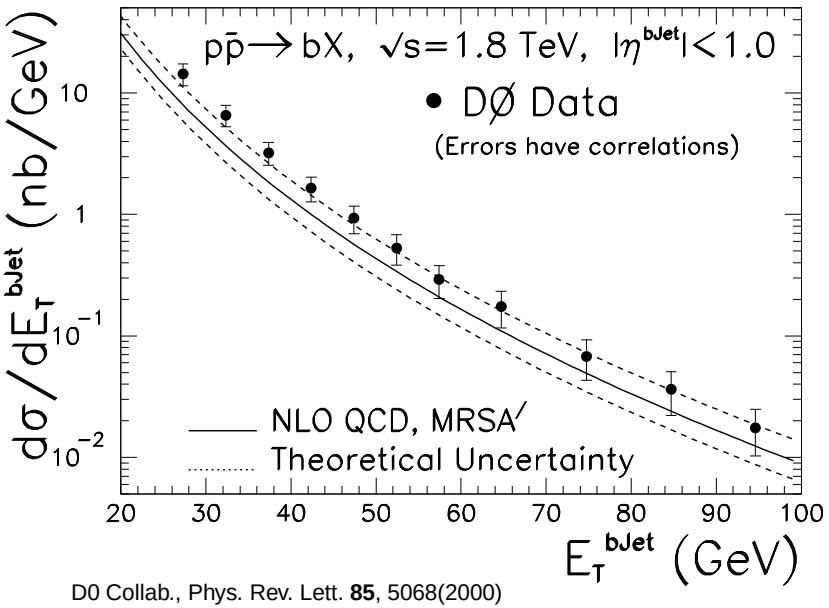


M.Cacciari,hep-ph/0407187



CDF Collab.,Phys. Rev. D **65**, 052005(2002)

$\Rightarrow$ D0 Run I inclusive b- jet cross-section measurements. b- jet are tagged by s.-l. b- decays.



D0 Collab., Phys. Rev. Lett. **85**, 5068(2000)

- The "excess"of experiment over theory was apparently established...
- Is it normalization or shape problems both in theory and data?
  - Total cross-section experimental data would be a good test for theory.
- Is it a problem of underestimated non-perturbative information hidden in convolutions on the way to the observables?
  - Non-perturbative contributions eventually are fitted from exp. data: PDF and FF.
- The charm sector was not yet probed in Run I – again a good candidate for further tests.

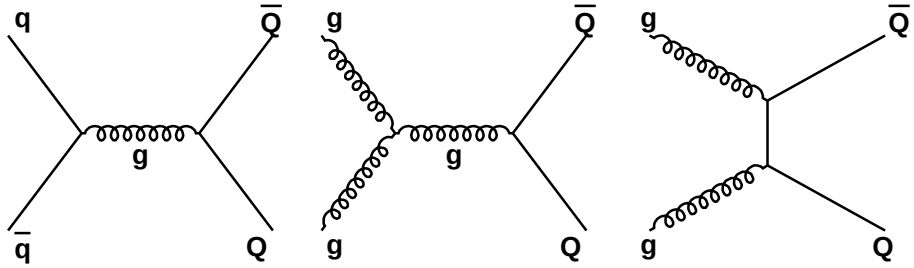
3 – Theoretical Approach to Heavy Quark Production

⇒ Production in Hadron

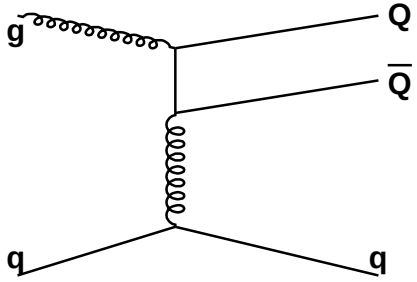
⇒ Collisions at Tevatron:

- Leading Order (LO) Diagrams.
- NLO: Flavor Excitation
- NLO: Gluon Splitting.
- $\mathbf{m_Q \gg \Lambda_{QCD}}$, where
- $\Lambda_{\mathrm{QCD}} \simeq 400\,\mathrm{MeV}$,
  typical scale of strong interactions.
- $\mathrm{m_Q} \simeq 1.5\,\mathrm{GeV},\ \mathrm{Q} \equiv \mathrm{c}.$
- $\mathrm{m_Q} \simeq 4.8\,\mathrm{GeV},\ \mathrm{Q} \equiv \mathrm{b}.$
- ... implies computing of x-section
  $d\hat{\sigma}(gg, gq, qq \to Q + X)$
  free of singularities.

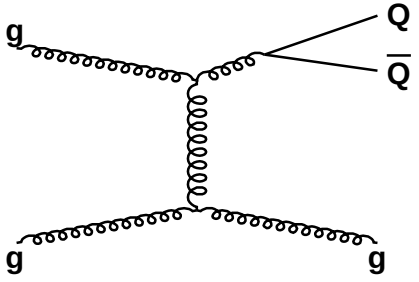
Lowest Order Tree Diagramms.



Flavour Excitation.



Gluon Splitting.



$\Rightarrow$ **Factorization:** separation of perturbative, $d\hat{\sigma}$ and

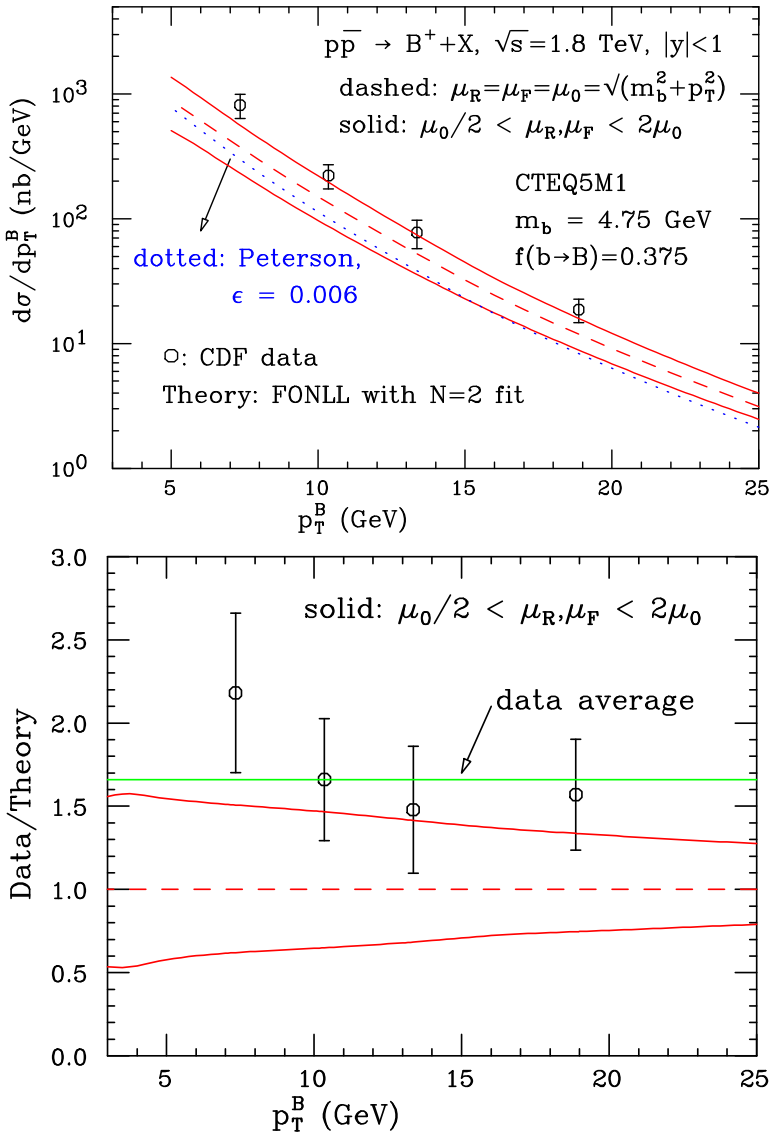
$\Rightarrow$ non-perturbative, $\mathcal{F}$ (or PDF) and $\mathcal{D}$ (or FF) contributions

$\Rightarrow$ $$\frac{\mathbf{d\sigma(p\bar{p}\rightarrow H_Q + X)}}{\mathbf{dp_T(H_Q)}} = \mathcal{F}^{\mathbf{p,\bar{p}\rightarrow q,g}} \otimes \frac{\mathbf{d\hat{\sigma}(gg,gq,qq\rightarrow Q + X)}}{\mathbf{dp_T(Q)}} \otimes \mathcal{D}^{\mathbf{Q\rightarrow H_Q}}$$

- Large logarithms in NLO, $\mathcal{O}({\alpha_S}^3)$ terms of $d\hat{\sigma}$, $\alpha_S \cdot \log(\mathcal{Q}^2)$, where $\mathcal{Q} = \frac{p_T(Q)}{m_Q}$ and $\mathbf{p_T(Q) \gg m_Q} \Rightarrow$ re-summation at Next-to-Leading-Log (NLL) level, considered as a perturbative part of $\mathcal{D}$ (data/theory moves $\sim +20\%$)
- The NLL formalism results to a changed functional form of Fragmentation Function (again $\sim +20\%$)
- The NLL formalism is used to extract the Non-Perturbative part of Fragmentation Function from e^+e^- data (ALEPH Collab., 2001) (another $\sim +20\%$)
- The fixed order (FO) calculations of $d\hat{\sigma}$ are merged with NLL $\Rightarrow$ FONLL technique.
- The cross-section is quite dependent from input of phenomenological (and essentially non-perturbative) structure functions or PDF, $\mathcal{F}$: e.g. $\sigma_b^{NLO}(|y| < 1)$ is up by $\sim 10\%$ from CTEQ5M to CTEQ6M

- **b-Production at Tevatron Revisited**
- **CDF Run I $B^+ \to J/\psi\, K^+$ (2001) over Theory Ratio**
- "The experimental points are compatible with predictions obtained using the present value of the QCD scale parameter and of the structure functions, and a b pole mass of 4.75 GeV, and lie near the upper region of the theoretical band obtained by varying the factorization and renormalization scales.", M.Cacciari,P.Nason, hep-ph/0204025
- Data/Theory ratio has changed from $2.9 \pm 0.2(stat \oplus sys) \pm 0.4(sys)$ to $1.7 \pm 0.5(exp) \pm 0.5(theory)$

M.Cacciari,P.Nason, hep-ph/0204025

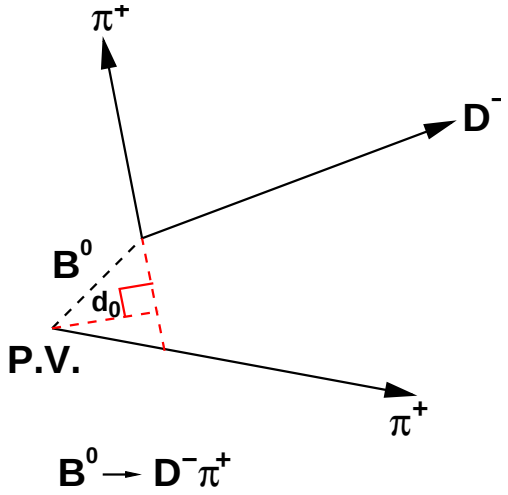


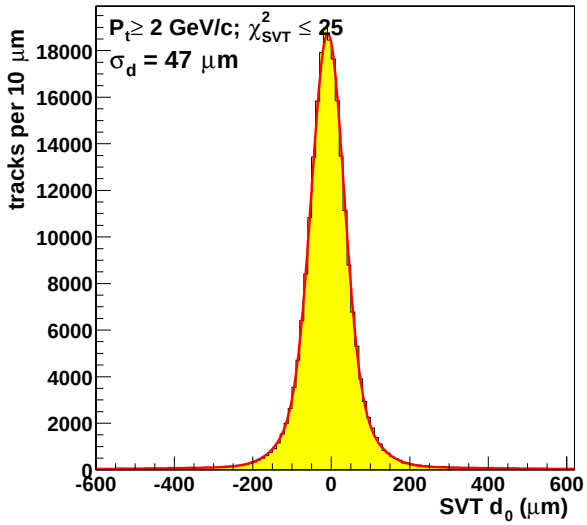
4 – Direct Charm Production in CDF II

⇒ **Trigger on Hadron Modes**

⇒ **of Heavy B-, D- Mesons, Baryons**

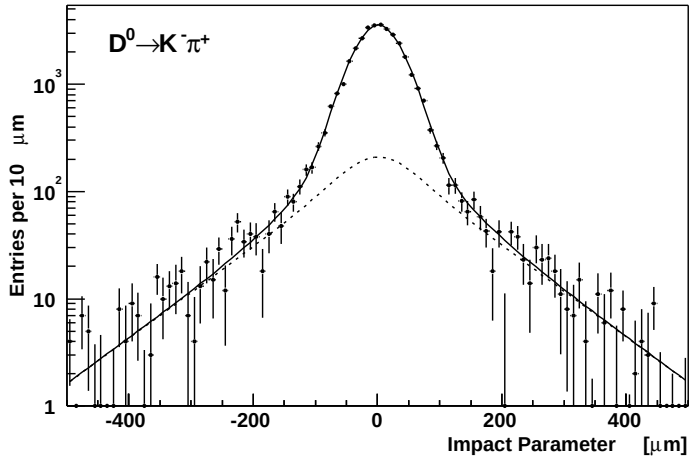
- Level 1 eXtremely Fast Tracker (XFT)
  Trigger: high p_T
- Level 2 Silicon Vertex Trigger (SVT):
  large track d_0
- impact parameter resolution by SVX II detector
  $\sigma(\mathrm{d_0}) = \sigma_{\mathrm{beam}} \oplus \sigma_{\mathrm{SVX}} = 48\mu\mathrm{m}$
- At a Level 3: a full event reconstruction.
- Improves Run I sensitivity by 4-5 orders of magnitude.
- Data sample is dominated by charm.



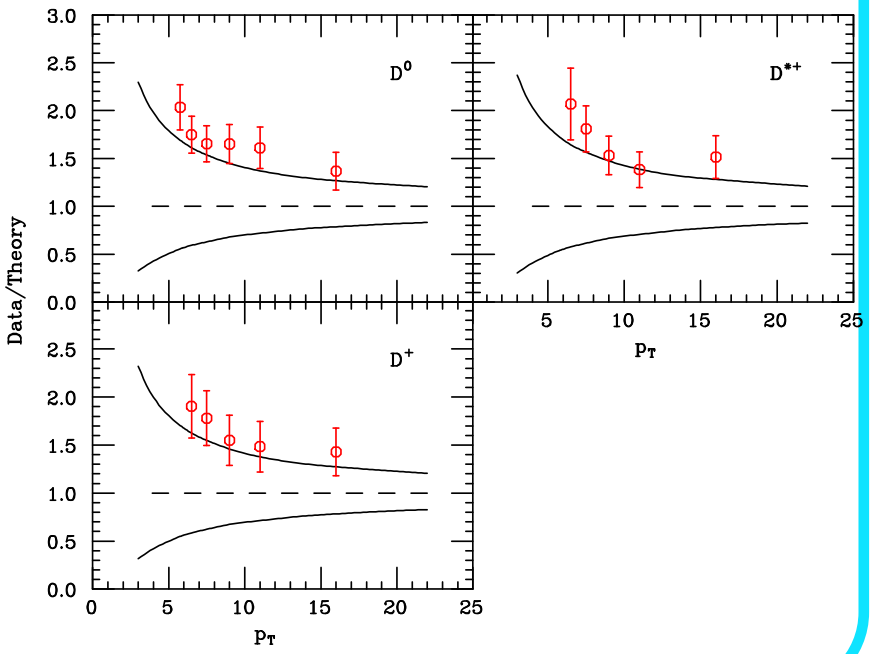


- Analyze shape of an impact parameter of reconstructed D-mesons $\Rightarrow$
- Separate the directly produced charm fraction (solid line) from b-decay products (dotted line) $\Rightarrow$
- Parameterize both contributions and fit.
- Fit finds the prompt fraction $\Rightarrow$ corr. for ϵ
- $\sigma(\mathbf{D^0}, p_T \geq \mathbf{5.5}\,\mathrm{GeV/c}, |\mathbf{y}| \leq \mathbf{1}) = \mathbf{13.3 \pm 0.2 \pm 1.5}\,\mu\mathrm{b}$
- $\sigma(\mathbf{D^+}, p_T \geq \mathbf{6.0}\,\mathrm{GeV/c}, |\mathbf{y}| \leq \mathbf{1}) = \mathbf{4.3 \pm 0.1 \pm 0.7}\,\mu\mathrm{b}$
- $\sigma(\mathbf{D^{*+}}, p_T \geq \mathbf{6.0}\,\mathrm{GeV/c}, |\mathbf{y}| \leq \mathbf{1}) = \mathbf{5.2 \pm 0.1 \pm 0.8}\,\mu\mathrm{b}$
- The agreement of CDF II data with FONLL calculations for charm sector is moderate, with data lying at the upper bound of theor.syst. $\Rightarrow$

CDF Collab., Phys. Rev. Lett. **91**, 241804(2003)



M.Cacciari,P.Nason, hep-ph/0306212

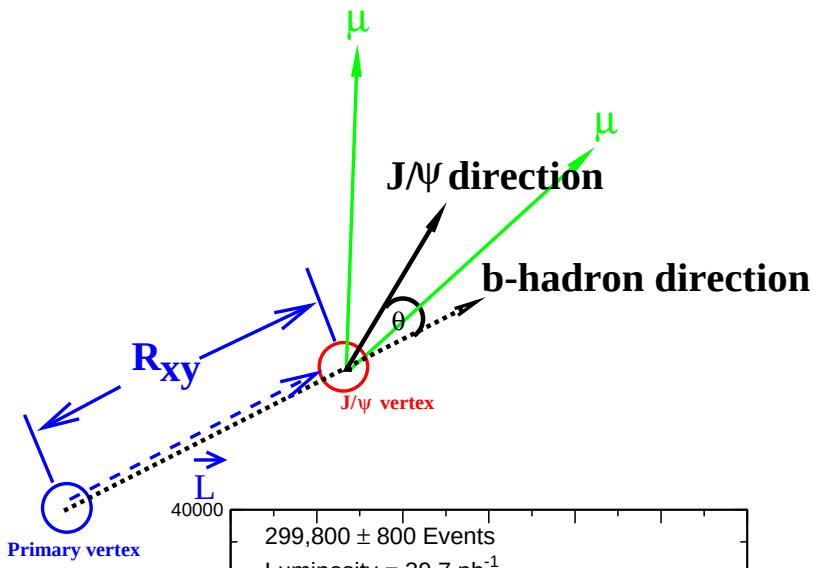


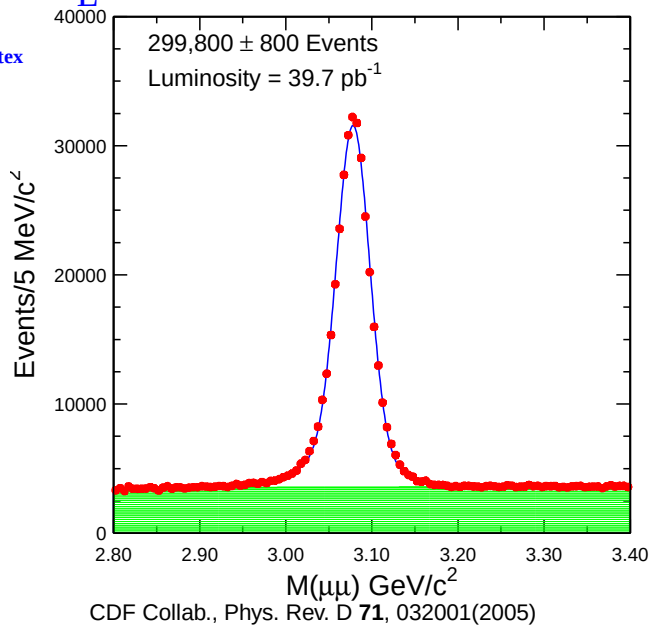
5 – Inclusive b- Hadron Production in CDF II

$\Rightarrow$ **Measure** $\mathbf{p\overline{p} \to J/\psi\, X}$

$\Rightarrow$ **Extract** $\mathbf{b \to J/\psi\, X}$

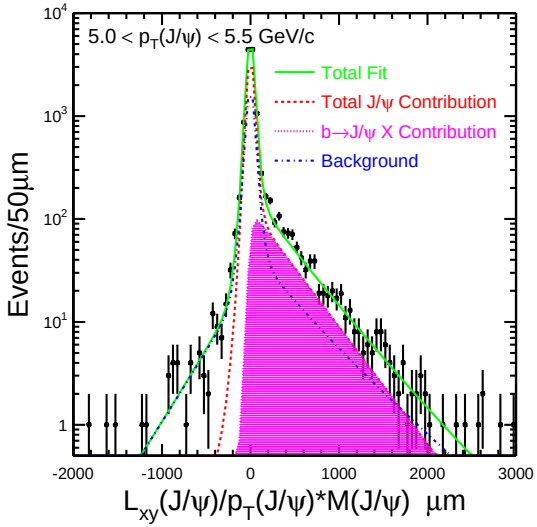
- Level 1 eXtremely Fast Tracker (XFT) Trigger: tracks are reconstructed in the COT and matched to hits in the Muon Chambers.
- Level 2: transparent
- Level 3: full reconstruction with cut $M(\mu^+\mu^-) \in [2.7, 4.0]\,\mathrm{GeV}/c^2$
- Lower $p_T(\mu)$ reach $\Rightarrow$ $p_T(J/\psi) \sim 0\,\mathrm{GeV}/c$
- Distinguish $B \to J/\psi\, X$ from prompt J/ψ applying fit to a flight path $L_{xy} = \vec{L} \cdot \vec{p_T}/|p_T|(J/\psi)$

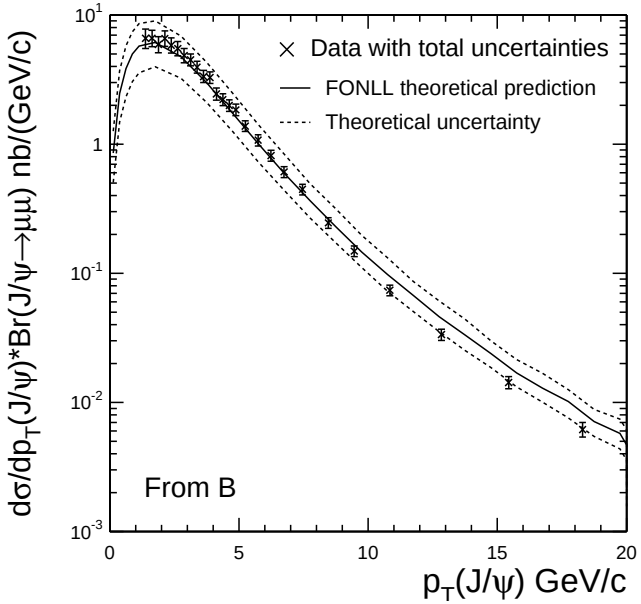




CDF Collab., Phys. Rev. D **71**, 032001(2005)

- Likelihood fit of pseudo-proper time $c\tau = L_{xy} \cdot (M/p_T)$ in bins of p_T $\Rightarrow$
  - Prompt J/ψ (including $\psi(2S)$).
  - Parameterized background.
  - fit finds $b \to J/\psi$ fraction,
  - e.g. $(14.1 \pm 0.5 \pm 0.6)\%$ $\Rightarrow$
- $\sigma(\mathbf{p\overline{p} \to H_b X, H_b \to J/\psi\, X, J/\psi \to \mu^+\mu^-, p_T > 1.25\,GeV/c, |y(J/\psi)| \leq 0.6}) = \mathbf{19.4 \pm 0.3^{+2.1}_{-1.9}\,nb}$
- Very good agreement with FONLL (M.Cacciari,hep-ph/0312132): $\sigma(\mathbf{J/\psi, FONLL}) = \mathbf{18.3^{+8.1}_{-5.7}\,nb}$
- Updated PDF CTEQ6M and b- FF brought QCD calculations into better $\Rightarrow$ agreement with our measurements of σ^b_{tot} and p_T distribution.





CDF Collab., Phys. Rev. D **71**, 032001(2005)

6 – Inclusive b- Jet Cross-Section Measurement in CDF II

$\Rightarrow$ Study $\mathbf{p\overline{p} \rightarrow Jet + X}$

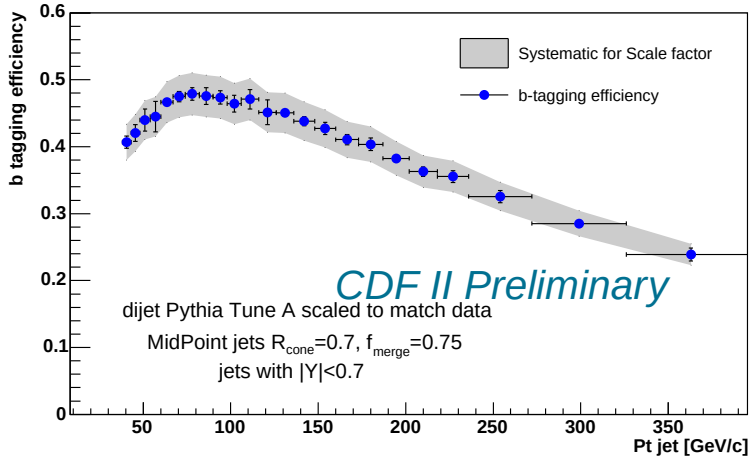
- Jets are good observables as the energy of most of fragmentation products is collected inside their cones. The measurements are less sensitive to heavy quark fragmentation. The predictions of NLO models are expected to be less sensitive as collinear gluons causing large $\log$-s are counted in jet cones.
- Jet triggers are very inclusive and non-biased to track reconstructed objects like secondary vertexes.
- Jet study extends a p_T reach beyond [1.25,25] GeV/c range accessible with exclusive decay modes.
- Use a MidPoint cone algorithm to reconstruct jets
  - Total luminosity used in the analysis: $\mathcal{L} \sim 300\,\mathrm{pb}^{-1}$
  - MidPoint jets with cone $R_{cone} = 0.7$, central jets with $|Y_{jet}| < 0.7$.
  - MidPoint adds an extra seed in a center of each pair of seeds.
  - p_T- range is [30, 360] GeV/c (before jet energy scale correction).

- Jet (or calorimetric) specific issues
  - Hadron Energy Scale of jets.
  - Correction for an ambient energy flow from Underlying Events
  - Unfolding of E_T experimental spectra to a hadron particle level jets.

$\Rightarrow$ **Tag Jet with Secondary VX.**

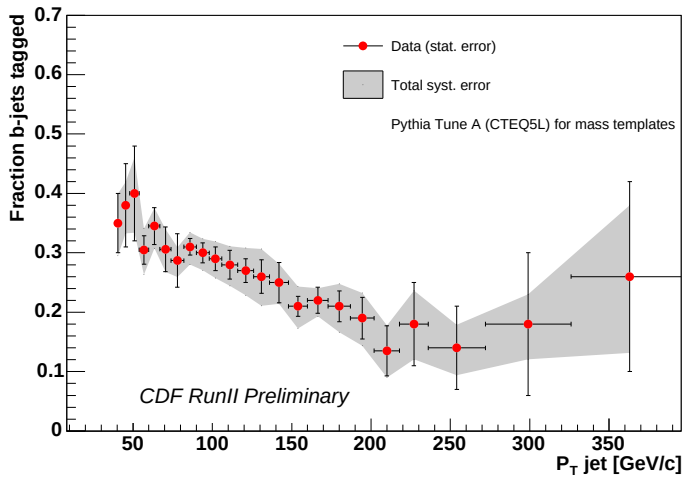
- Exploit a tracking information: match tracks with jet cones.
- The tracks are required to have displaced impact parameter in $x-y$ transversal plane:
  - $3 \cdot \sigma_{d_0} < d_0 < 0.3\,\mathrm{cm}$
  - Fit the tracks to a common secondary vertex, $secVX$
- B- hadrons have a $c\tau \sim 450\,\mu\mathrm{m}$.
  - Require a significance $L_{xy}/\sigma_{L_{xy}} > 3.0$.
- The jet is “positively” tagged.

$\Rightarrow$ b- Tagging Efficiency ϵ_{bTag}.



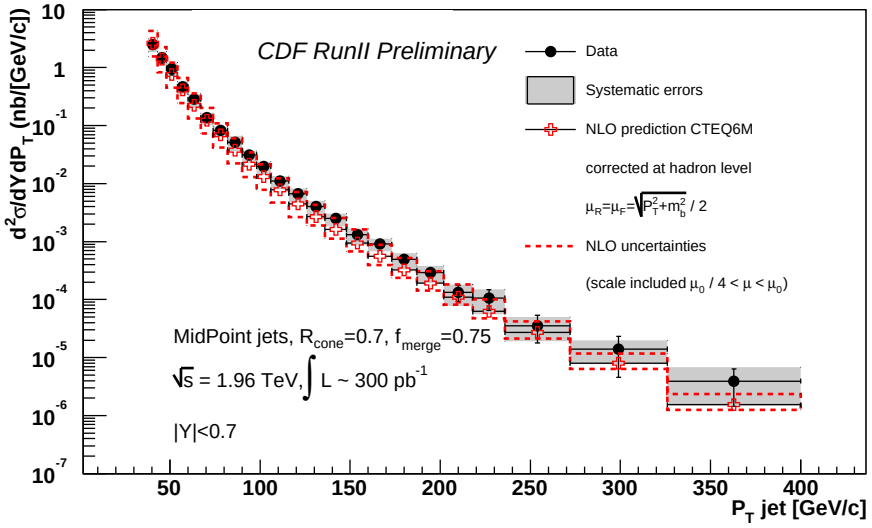
- Use MC simulation to calculate ϵ_{bTag}^{MC} over $[38, 360]\,\mathrm{GeV}/c$
- Measure ϵ_{bTag}^{Data} using a b- enriched inclusive electron $E_e > 8\,\mathrm{GeV}/c$ data sample covering only $[15, 60]\,\mathrm{GeV}/c$.
- Then ϵ_{bTag}^{MC} is corrected by $SF = \epsilon_{bTag}^{Data}/\epsilon_{bTag}^{MC} = 0.909 \pm 0.06$

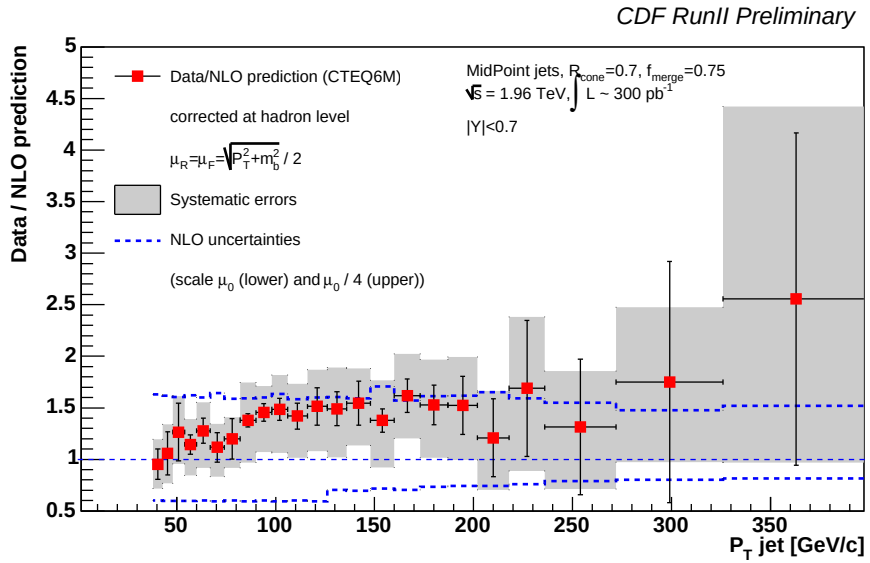
$\Rightarrow$ b- Fraction f_b in Tagged Jets.



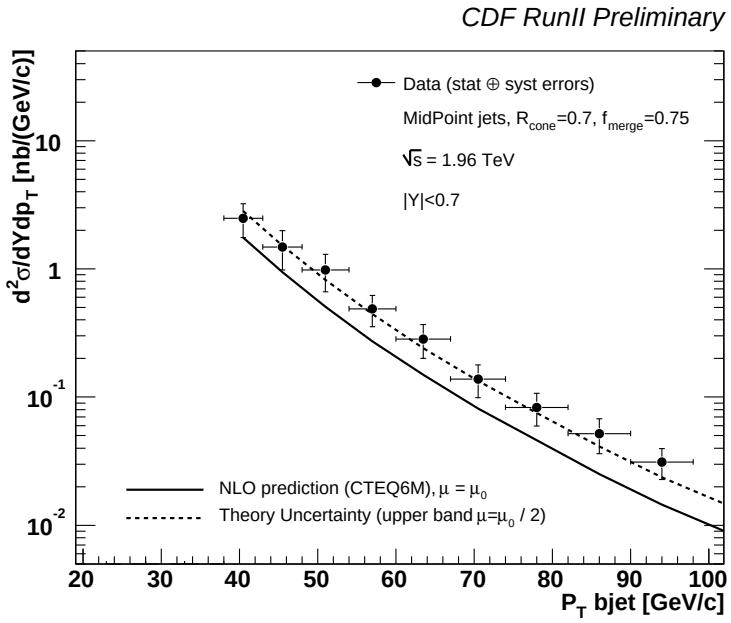
- The tagged jet is likely to contain a decay vertex of b-, c- or light quarks (e.g. s- quark).
- Again f_b has to be extracted.
- Fit $\mathcal{M}_{secVX}$ distribution to MC templates of b- and non b- components of positively tagged jets.
- Fit finds an f_b for tagged jets.
- Proceed for every p_T- bin.

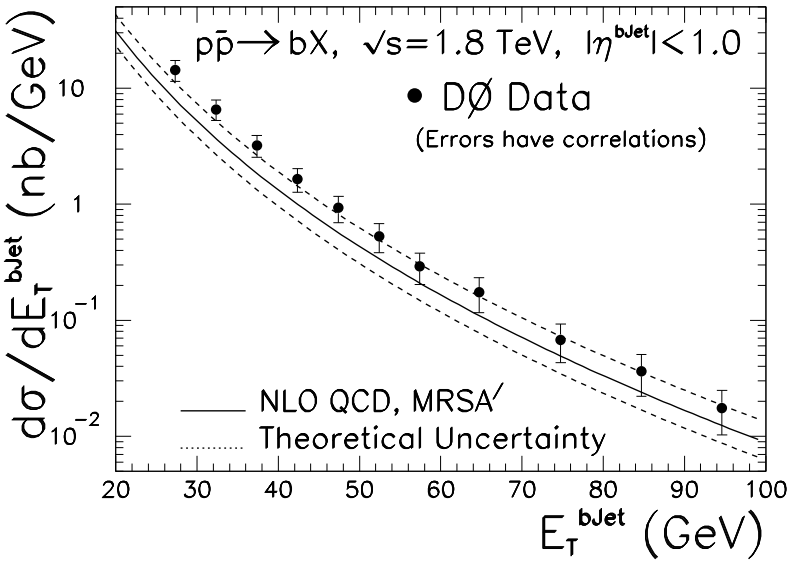
- **Preliminary CDF II Results on (central) b- jet cross section measurement.**
- Compare experiment with NLO predictions by M. Mangano & S. Frixione.
- The NLO predictions are made at the hadron level.
- The theoretical syst. includes PDF (CTEQ6M) and jet clustering uncertainties of $\sim 10\%$.
- **The data points are overshooting theory, but...**
- **Agreement within NLO uncertainties.**





- Compare presented preliminary CDF II results with Run I D0 measurements of b- jet production.
- Plot CDF Run II points below 100 GeV/c. The NLO predictions are made at $\mu_R = \mu_F = \mu_0, \mu_0/2$
- CDF II results show a very similar pattern w.r.t. theoretical predictions as Run I D0 measurements.





7 – Conclusions

- **A vigorous efforts on a theoretical understanding and experimental measurements of Heavy Quark Production spectra have been demonstrated by parties of both experimentalists and theorists.**
- **The measurements and calculations revealed a wonderful trend of a convergence of their central values.**
- **CDF II Collaboration has published first measurements of direct charm production cross-section spectra of D- mesons reconstructed in hadron modes. These results motivated further developments of QCD approaches applied before only to a bottom species.**
- **CDF II has advanced the b- production measurements both to a low $\mathbf{p_T}$ and high $\mathbf{p_T}$ ends of a b- spectrum.**
  - **b- production in $\mathbf{b \rightarrow J/\psi + X}$ mode has been published up to $\mathbf{p_T}$ as low as 1.25 GeV/c and as high as 20 GeV/c**

- **CDF II has presented a preliminary results on central production of b-tagged jets in a wide range extended from 38 GeV/c to 360 GeV/c.**
- **CDF II measurements are in agreement with theoretical QCD NLO calculations within experimental and theoretical uncertainties.**

THE END OF THE TALK.